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A STUDY OF THE EFFECTS OF ENVIRONMENTAL NOISE ON THE PERFORMANCE OF FLUID AMPLIFIERS

THESIS

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ENVIRONMENTAL NOISE ON

THE PERFORMANCE OF

FLUID AMPLIFIERS

THESIS

Presented to the Faculty of the School of Engineering of

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by

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Preface

This study, originally proposed by Mr. Seth A. Young of the Avionics Laboratory, Wright-Patterson AFB, Ohio, is the first known investigation of the effects of environmental noise on fluid amplifiers. It is my hope that the results of this study will prompt others to continue the investigation of these effects.

I wish to express my appreciation to the Avionics Laboratory which sponsored this study, and to the Aero-Acoustics Branch of the Air Force Flight Dynamics Laboratory which provided the testing facilities for this study. Also, I wish to thank my thesis advisor, Professor Milton E. Franke, for his guidance and suggestions in overcoming obstacles during the progress of my work.

Charles Jasper Hansen, Jr.

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List of Symbols

f	frequency
P_{lc}	left control pressure
P_{rc}	right control pressure
P_{lo}	left output pressure
P_{ro}	right output pressure
ΔP_c	$P_{lc} - P_{rc}$
ΔP_{c1}	switching differential control pressure - left to right
ΔP_{c2}	switching differential control pressure - right to left
P_s	amplifier supply pressure (gage)
SPL	sound pressure level (rms)
Q	amplifier volumetric flow rate

Abstract

The effects of environmental noise on the static performance of two bistable fluid amplifiers were studied. Plots of differential control pressure versus differential output pressure were made by varying input pressure to one control. In addition to sound frequency and pressure level, variables considered included amplifier configuration, orientation, and supply pressure. Tests were run at frequencies of 100, 200, 500, 1000, and 2000 cps and sound pressure levels ranging from 151 to 157 db.

The effects noted varied widely and included decreased hysteresis, instability, and complete loss of bistable characteristics. The phenomena of jet spreading, radiation pressure, and acoustic streaming were related to these effects. Recommendations were made for further study in this area.

A STUDY OF THE EFFECTS OF ENVIRONMENTAL NOISE ON THE PERFORMANCE OF FLUID AMPLIFIERS

I. Introduction

Statement of the Problem

The purpose of this study was to investigate the effects of environmental noise on the performance of fluid amplifiers.

Background

Fluid amplifiers have demonstrated a high degree of tolerance to extremes of temperature and vibrational shock. Therefore, it appears likely that they will be used in military and space applications where high levels of environmental noise will be encountered.

Considerable information has been published relating acoustics to fluid motion (Refs. 1,2). Of primary interest to this study are reports on experiments which were conducted at Harry Diamond Laboratories in 1963 and 1964.

One of these experiments, using a jet and offset wall (Appendix A), demonstrated the effects of sound on the jet attachment point (Ref. 3). It was noted that acoustic streaming (Ref. 5) increased the velocity of the jet and caused the attachment point to move downstream.

In two experiments the use of acoustic inputs to switch

bistable amplifiers was demonstrated (Refs. 3,4). Acoustic streaming caused the jet attachment point to move downstream, and radiation pressure (Ref. 8) was sufficient to cause switching. Data was obtained to show that it required less acoustic power than pneumatic power to cause switching. Considerable jet spreading was also noted as evidenced by a decrease in differential output pressure.

Scope and Approach

The most common fluid amplifier employing the wall attachment principle, the bistable flip-flop (Fig. 1) was chosen for this study. From several of these devices loaned by private industry, two were chosen for testing.

Performance tests for bistable amplifiers can be classified broadly as either dynamic or static. Dynamic testing

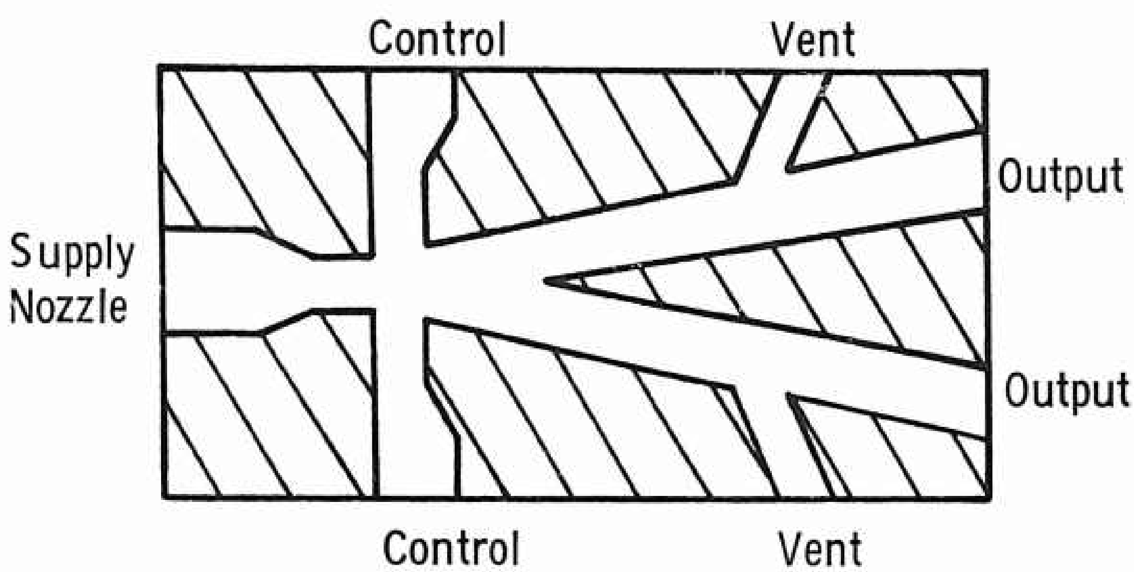

FIG. 1
Bistable Flip-Flop Amplifier

is used to determine amplifier response time with square wave or sine wave control pressure inputs, while static testing is used to determine pressure and flow conditions in steady state operation and to determine the control pressure and/or flow rate required to cause switching.

Because of the relative ease of instrumentation and control, static testing to determine the control pressure required to cause switching was judged most appropriate for this study. Although many versions of this test are possible, they all give an indication of the hysteresis or "memory" of a bistable element. By comparing the hysteresis of an amplifier under normal conditions with its hysteresis in a noise environment, an indication of the effects of the noise can be obtained.

Since the effects of noise were expected to be frequency dependent, testing was conducted using pure tone sound rather than wide band noise. Provisions were also made to control the orientation of the amplifiers to the sound source.

II. Apparatus and Procedure

Test Apparatus

The equipment used to control the fluid amplifiers and measure pressures and flow rates is shown schematically in Fig. 2. Differential strain gage pressure transducers were connected so as to give measurements of $(P_{lc} - P_{rc})$ and $(P_{lo} - P_{ro})$. The transducer output leads were connected to an x-y recorder where amplifier performance was displayed. Another pressure transducer which was connected to a millivoltmeter was used to measure P_s. Upstream of this transducer a rotometer was included to measure volumetric rate of flow. Precision pressure regulators were used in lieu of valves to vary supply and control pressures.

Sound for preliminary tests was supplied by a loudspeaker. Wide band noise was filtered to one sixth octave either side of the desired frequency and amplified to produce the driving signal for the loudspeaker. The fluid amplifiers were suspended inside the loudspeaker horn with rubber bands. Sound intensity was measured with a portable sound pressure level meter.

Sound for the primary tests was supplied by an air driven siren at the Aero-Acoustics Branch of the Air Force Flight Dynamics Laboratory. The siren, capable of producing frequencies up to 2000 cps, discharged into a 1 ft square duct. In order to isolate the experiment from the air blast, a wooden chamber, insulated to minimize reverberation, was mounted on the side of the duct as shown in

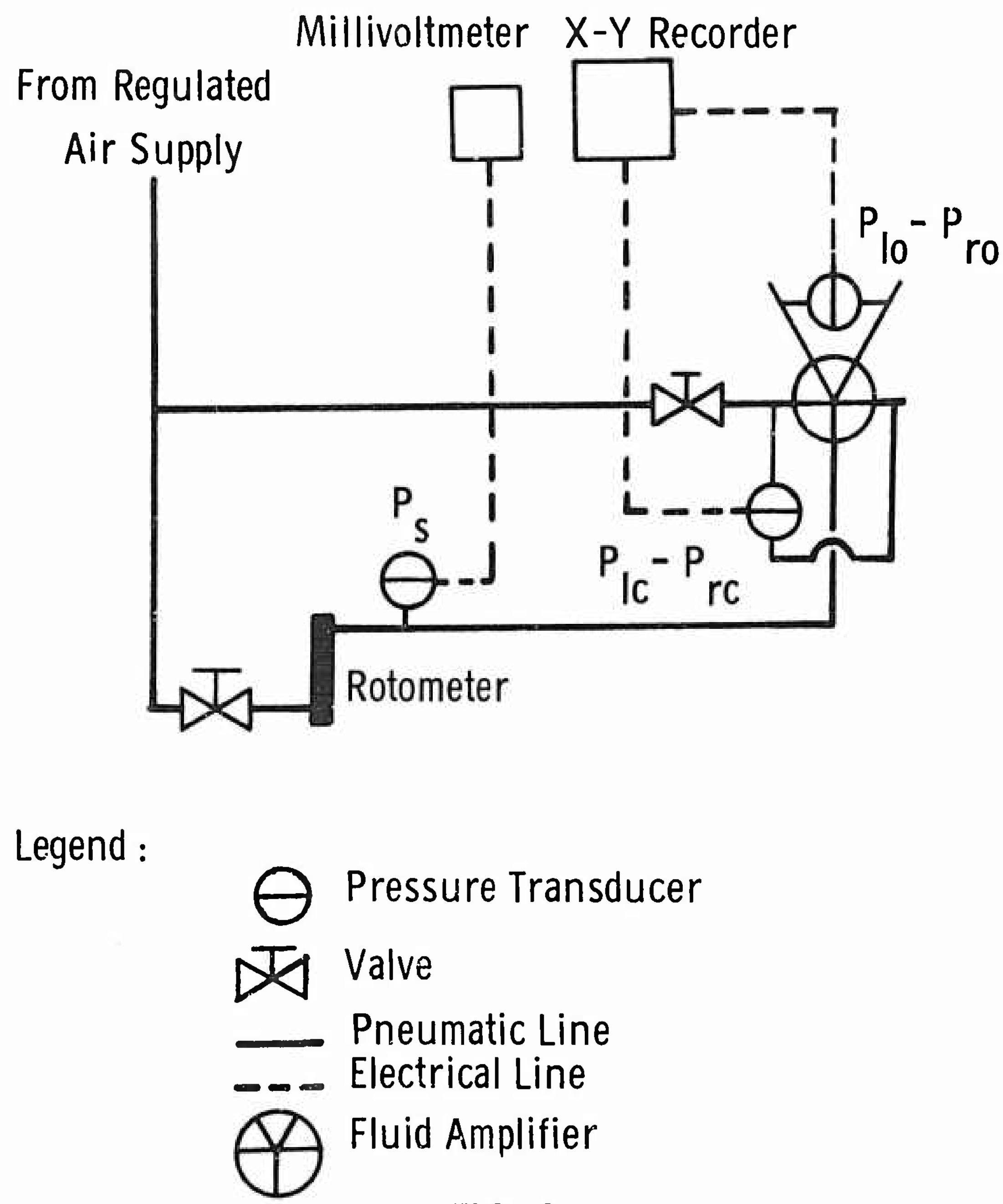

FIG. 2

Schematic Diagram Of Experimental Setup

Fig. 3. Sound entered the chamber through a 5 in. square hole. The pressure transducers were mounted adjacent to the chamber with precautions taken to minimize mechanical vibrations.

The fluid amplifiers were suspended inside the chamber with rubber bands. The plastic pneumatic tubing used was relatively stiff. When the tubing was inserted through holes in the side of the box, and connected to the amplifiers, this stiffness permitted the amplifiers to be oriented as desired.

Measurements of sound frequency and pressure level were taken with a microphone mounted inside the chamber. The microphone was connected to a frequency spectrum analyzer which, when activated, automatically recorded SPL versus frequency from 0 to 40,000 cps.

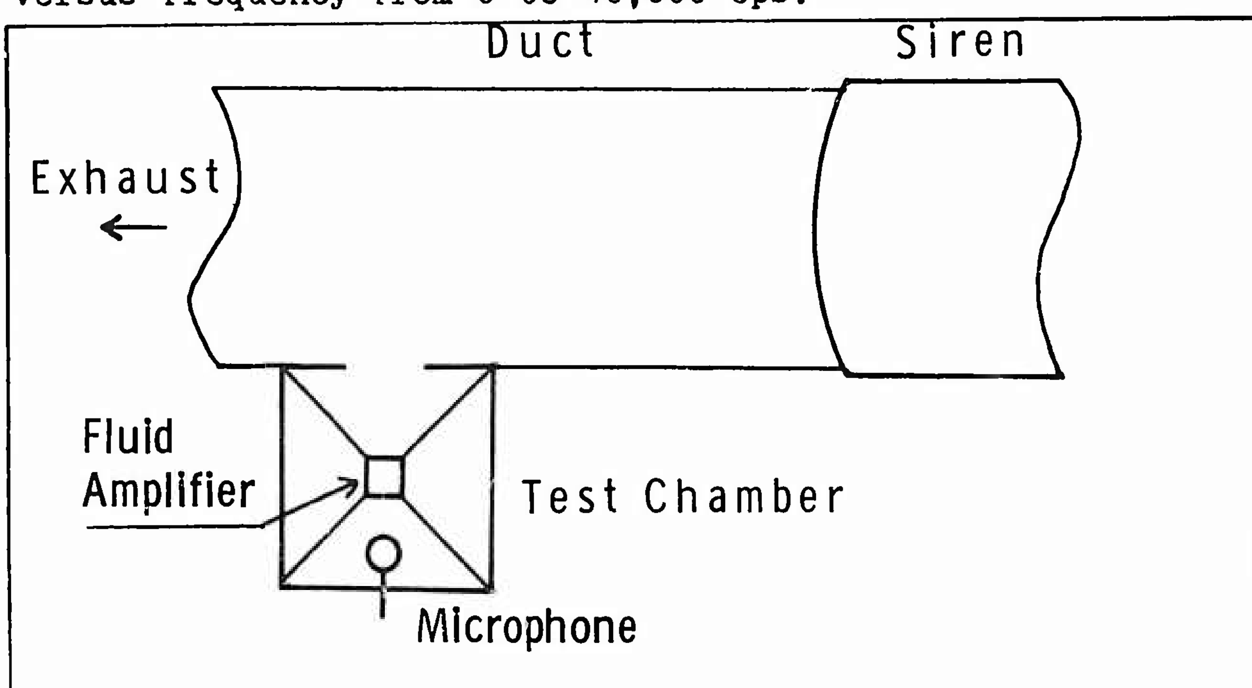

FIG. 3

Test Chamber Location-Top View

Test Procedure

The first step in each run was to place the fluid amplifier into operation at the desired supply pressure and configuration, and record its static performance. With the right control open to the atmosphere and the valve in left control line closed, the jet would attach to the left wall of the amplifier. The valve was then opened slowly increasing (P_{lc} - P_{rc}). When the jet switched to the right wall, there was a sudden decrease in (P_{lo} - P_{ro}). The valve was then closed slowly, decreasing (P_{lc} - P_{rc}). When the jet returned to the left wall, there was a sudden increase in (P_{lo} - P_{ro}). These changes in differential control and output pressures are shown graphically in Fig. 4.

At the instant the jet switched from a wall there was a sudden rise in pressure at the control port adjacent to the wall. This, coupled with the lag and overshoot of the x-y recorder, resulted in graphs similar to Fig. 5.

During the tests using the loudspeaker, the wide band noise was filtered as desired and amplified to produce the driving signal. The sound intensity was measured, and a plot of the static performance of the fluid amplifier was obtained using the procedure previously described. This procedure was repeated for several amplifier orientations at frequencies ranging from 100 to 10,000 cps.

During the tests using the siren, maximum air pressure was applied to the siren with the modulator locked, and a

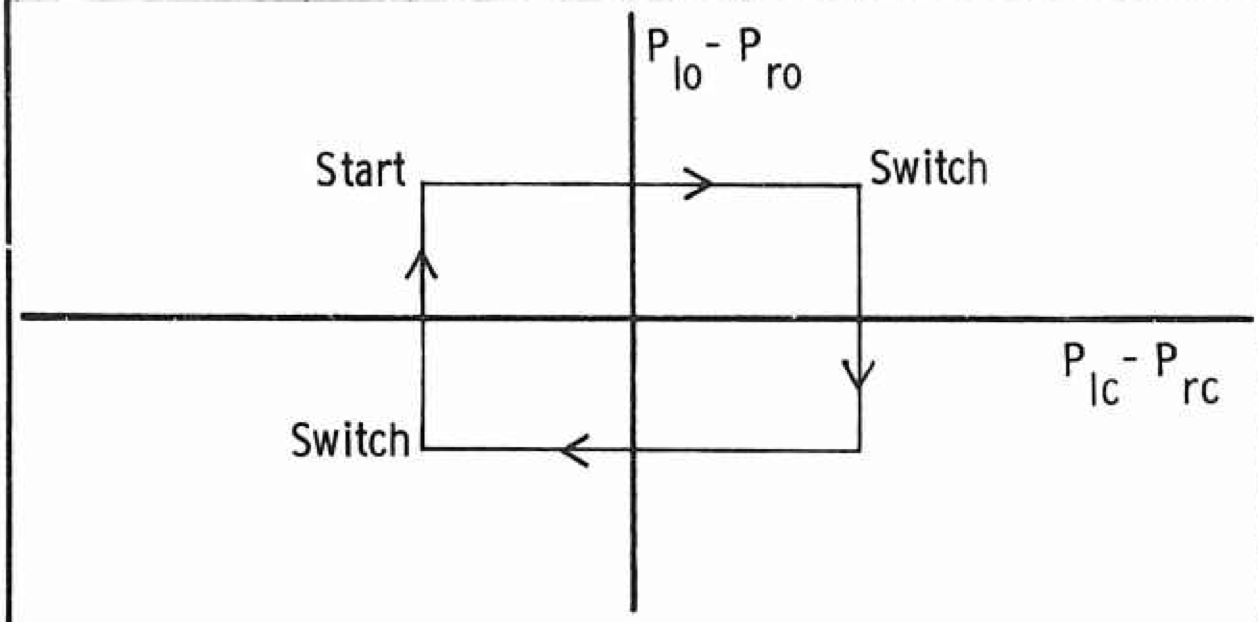

FIG. 4

Ideal Hysteresis Loop

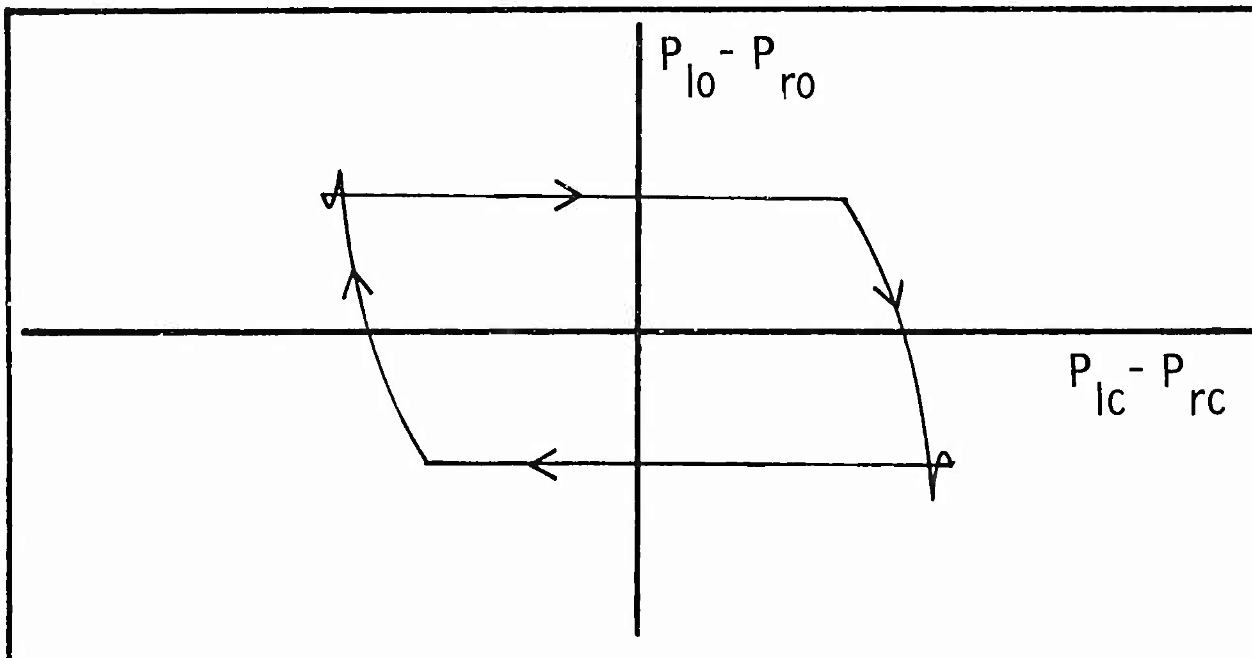

FIG. 5

Actual Hysteresis Loop

check was made to insure that the air flow in the duct had not affected the static performance of the amplifier.

The air pressure to the siren was then decreased and the modulator was unlocked and set at the desired frequency. The air pressure was then increased to bring the sound pressure level inside the test chamber to the desired level. Possibly due to the characteristics of the test chamber, the maximum sound pressure level achieved at 2000 cps was lower than the maximum sound pressure level possible at lower frequencies. Therefore, each test began with the siren at 2000 cps, and all runs at lower frequencies were made at the maximum sound pressure level obtained at 2000 cps.

When the siren stabilized at the desired frequency, the automatic frequency spectrum analyzer was activated, and a plot of the static performance of the fluid amplifier was obtained using the procedure previously described.

One fluid amplifier, hereafter refered to as amplifier "A", was tested at supply pressures of 8 and 32 in. Hg gage at frequencies of 2000, 1000, 500, 200, and 100 cps. During all tests on this amplifier, the outputs were loaded with a 0.0003 sq in. orifice to simulate the loading which would have resulted had similar fluid amplifiers been connected downstream. The configurations tested were:

1. Right control directed towards noise, outputs discharging outside test chamber.
2. Right control directed away from noise, outputs discharging outside test chamber.

3. Outputs directed towards noise, right control vented outside chamber.
4. Outputs discharging outside test chamber, right control vented outside test chamber.

The other fluid amplifier, amplifier "B", was tested at a supply pressure of 4 in. Hg at frequencies of 2000, 1000, 500, 200, 150, and 100 cps. The outputs were loaded with a 0.001 sq in. orifice. For reasons explained later, this amplifier was tested at two sound pressure levels in only one configuration: right control vented outside chamber, outputs directed towards noise.

III. Discussion of Results

Introduction

During the tests using the loudspeaker, sound pressure levels from 120 db to 140 db were obtained. No significant changes in fluid amplifier performance were noted during these tests.

The results of the tests using the siren are shown graphically in Appendix B, and are tabulated in Appendix C. Much higher sound pressure levels were obtained using the siren and the effects of noise on the performance of the fluid amplifiers varied widely with frequency and configuration. In most cases the amplifiers exhibited reduced hysteresis. However, there were some exceptions which could be separated into three classes: 1. Output proportional to control input. 2. A definite switch from left output to right output followed by a region of instability. 3. A cyclic switching from left output to right output over a wide range of differential control pressures.

Decreased Hysteresis

In general when the static tests resulted in a normal hysteresis loop, switching occurred at lower absolute values of differential control pressure. This is probably caused in part by acoustic streaming. Previous studies (Refs. 3,6,7) indicate that acoustic streaming reduces the area of a jet thereby increasing its velocity. This increase in jet velocity in a fluid amplifier would move the

attachment point downstream and reduce the stability of the amplifier. It would then require a smaller increase in control pressure to cause switching.

Output Proportional to Input

During the runs in which the amplifier output was proportional to the control input, (e.g., Fig. B-1, Right Control Towards Noise, P_s=8 in. Hg, f=1000 cps), sound evidently spread the jet to such a degree that it came into contact with both the right and left walls simultaneously. During the runs with amplifier B at f=2000 cps, SPL=157 db, the jet was stable on one wall or the other except in the small region where switching would normally occur. In this region the output was proportional to the control input, again indicating considerable jet spreading.

Instability

During the runs in which the jet switched from left to right and then remained unstable, (e.g., Fig. B-1, Outputs Toward Noise, P_s=8 in. Hg, f=2000 cps), the instability was noted to be random. One possible answer as to the cause of this instability lies in the phenomenon known as radiation pressure (Ref. 8). Any obstacle in the path of an acoustic wave experiences this pressure in addition to the equilibrium pressure. When the amplifier jet switches from left to right, an attachment bubble is formed between the jet and the right wall. If this bubble is seen as an obstacle by the acoustic waves, radiation pressure would increase the

pressure in this region. Although radiation pressure is generally treated as a second order effect, its presence along with the instability caused by acoustic streaming and jet spreading could possibly cause the jet to start to switch from right to left. At this point the flow through the left control would force the jet to return to the right wall.

Cyclic Switching

Radiation pressure might also explain the cyclic switching noted in several runs (e.g., Fig. B-1, Right Control Towards Noise, P_s=32 in. Hg, f=2000 cps). The higher supply flow rates for these runs would cause the jet attachment point to move downstream. Also, considerable jet spreading occurred as evidenced by the decrease in differential output pressure. With the stability of the amplifier thus reduced, radiation pressure could have caused switching to occur several times each second, giving the appearance of cyclic switching.

Additional Results

The results obtained on amplifier A show that the least effect occurred when only the vents were exposed to noise. Since the vents lead from the output legs, one would expect effects similar to those which occurred when the output legs were directed toward the noise. However, the vents on this amplifier did not lead directly to the sides of the amplifier, but terminated in ports drilled

completely through the amplifier. This construction feature could have minimized the effects of noise on the vents.

Since amplifier B was tested at two sound pressure levels, a study of Fig. B-2 and Tables C-9 and C-10 reveals the effects of doubling the sound intensity. At 151 db only reduced hysteresis occurred, while at 157 db, instability occurred at 500 cps and output was proportional to control input at 100 cps and 2000 cps.

Limitations

Several test configurations were planned for amplifier B. However, the epoxy bonding between the amplifier and its pneumatic fittings failed, possibly due to sonic vibrations.

Prior to the start of the formal test runs, it was noted that the performance of the fluid amplifiers was wildly disturbed by sound at frequencies below 50 cps. However, the test chamber was not able to withstand frequencies below 100 cps at high sound pressure levels.

Although the siren was described as a pure tone device, strong harmonics were occasionally present in the sound spectrum. This was especially true when operating at 500 and 1000 cps. At these frequencies first and second harmonics were generally present at a sound pressure level within 3 to 6 db of that of the desired frequency.

IV. Conclusions

Environmental noise does affect the performance of bistable fluid amplifiers. The effects vary with frequency, sound pressure level, and orientation of the noise to an amplifier. The phenomena of acoustic streaming, radiation pressure, and jet spreading help explain some of the effects noted, but much work remains to be done in this field.

V. Recommendations

The following recommendations are made:

1. Further testing along the lines described in this study should be made to include a greater sampling of frequencies over a wider range of the sound spectrum. Piezoelectric pressure transducers should be added to the test setup to obtain more data on dynamic effects.
2. Large scale models of fluid amplifiers should be obtained and instrumented to obtain pressure and flow measurements at many internal locations.
3. Transparent amplifiers should be obtained to permit flow visualization studies. Since the more common optical flow visualization setups are very sensitive to mechanical vibrations, the most promising approach appears to be the use of a birefringent gas to view photoviscous effects.
4. In order to give the researcher more control over the noise environment, future experiments should use a noise source that can be operated by the researcher himself. Two such noise sources are described in Ref. 9.

Bibliography

1. TR-1304. Fluerics, A Bibliography. Washington: Harry Diamond Laboratories, U. S. Army Materiel Command, 30 August 1965, pp. 121-143.

2. Powell A., and Smith, T.J.B. An Aerosonics Bibliography. Univ. of Calif., Los Angeles, Calif., Oct. 1963.

3. Gottron, R. N. "Acoustic Control of Pneumatic Digital Amplifiers." Proceedings of the Fluid Amplification Symposium. Vol 1, May 1964. Washington: Harry Diamond Laboratories, U. S. Army Materiel Command, pp. 280-291.

4. Gottron, R. N., R-RCA-64-4. Some Experiments with Acoustic Inputs to Pneumatic Amplifiers. Washington: Harry Diamond Laboratories, U. S. Army Materiel Command, 12 March 1964, pp. 1-4.

5. Andrade, E. N. da C., "On the Circulation Caused by the Vibration of Air in a Tube." Proc. Roy. Soc., A 134: 445-470 (1931).

6. Gottron, R. N., Deadwyler, R., R-RCA-63-16. The Effect of Sound on a Jet. Washington: Harry Diamond Laboratories, U. S. Army Materiel Command, 7 May 1963.

7. Gottron, R. N., R-RCA-63-23, Changes of Mean Pressure and Velocity in a Gas Due to Acoustic Wave Propagation. Washington: Harry Diamond Laboratories, U. S. Army Materiel Command, 23 August 1963.

8. Lindsay, R. B. Mechanical Radiation. New York: McGraw-Hill Co., 1960.

9. Soehngen, E. E., Holmann, J. P., ARL Tech. Rept. 60-323, Experimental Studies on the Interaction of Strong Sound Fields with Free Convection Boundary Layers. Wright-Patterson AFB: Aeronautical Research Laboratory, U. S. Air Force, October 1960.

Appendix A

The Wall Attachment Principle

The Wall Attachment Principle

Because of the high shear at the edges of a jet, fluid is entrained from the ambient. If a wall is located near a jet, the pressure in the region between the jet and the wall is lowered, and the resulting pressure gradient across the jet forces the jet to attach to the wall. With two walls present, the jet can attach to either wall and is stable in either attached position.

The region between the jet and the wall to which it is attached, upstream of the attachment point, is known as the attachment bubble. If the pressure in this bubble is increased sufficiently using a control channel, the jet can be made to attach to the opposite wall.

Appendix B

Scaled Reproductions of X-Y Recorder Data

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FIG. B-I

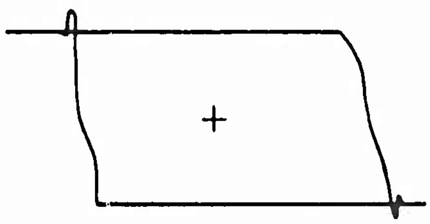
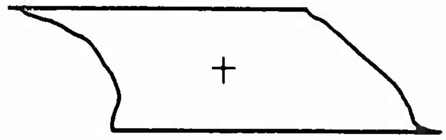
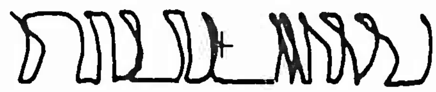
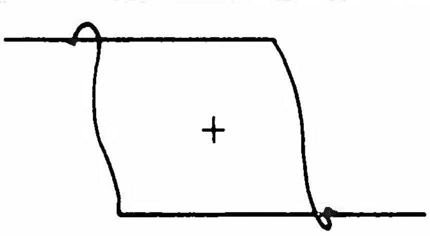
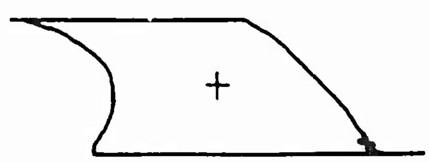
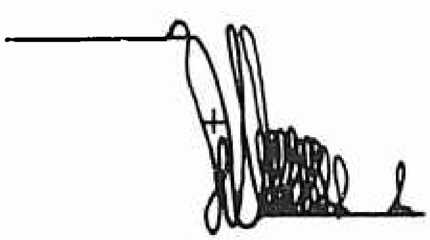
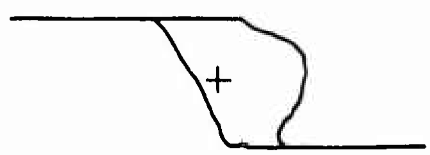
Scaled Reproduction of X—Y Recorder Data

"AMPLIFIER A"

ABSCISSA	P_{lc} - P_{rc}
Scale:	I in. = 0.3 in. Hg
ORDINATE	P_{lo} - P_{ro}
Scale:	
P_s = 8 in. Hg,	I in. = 6 in. Hg
P_s = 32 in. Hg,	I in. = 30 in. Hg

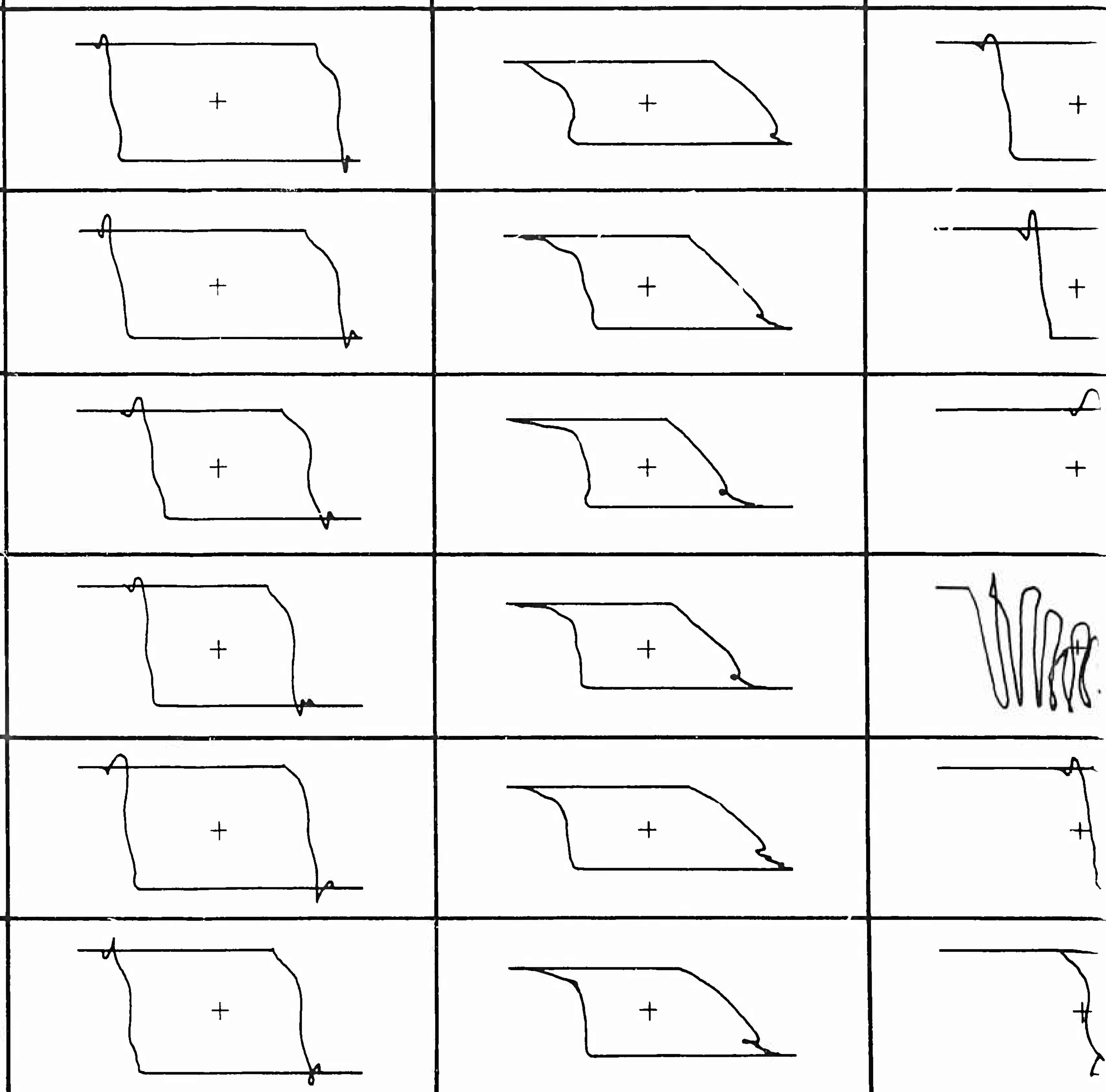
+ INDICATES 0, 0

A

CONFIGURATION / SPL / P_s / Q \ f CPS	RIGHT CONTROL TOWARDS NOISE SPL 152 db	
	P_s = 8 in. Hg Q = 1680 cc/min	P_s = 32 in. Hg Q = 2620 cc/min.
0		
2000		
1000		
500		
200		
100		

B

	VENTS TOWARD NOISE SPL 157 db		RIGHT
	P_S = 8 in. Hg Q = 1680 cc/min.	P_S = 32 in. Hg Q = 2620 cc/min.	P_S = 8 in Q = 1680

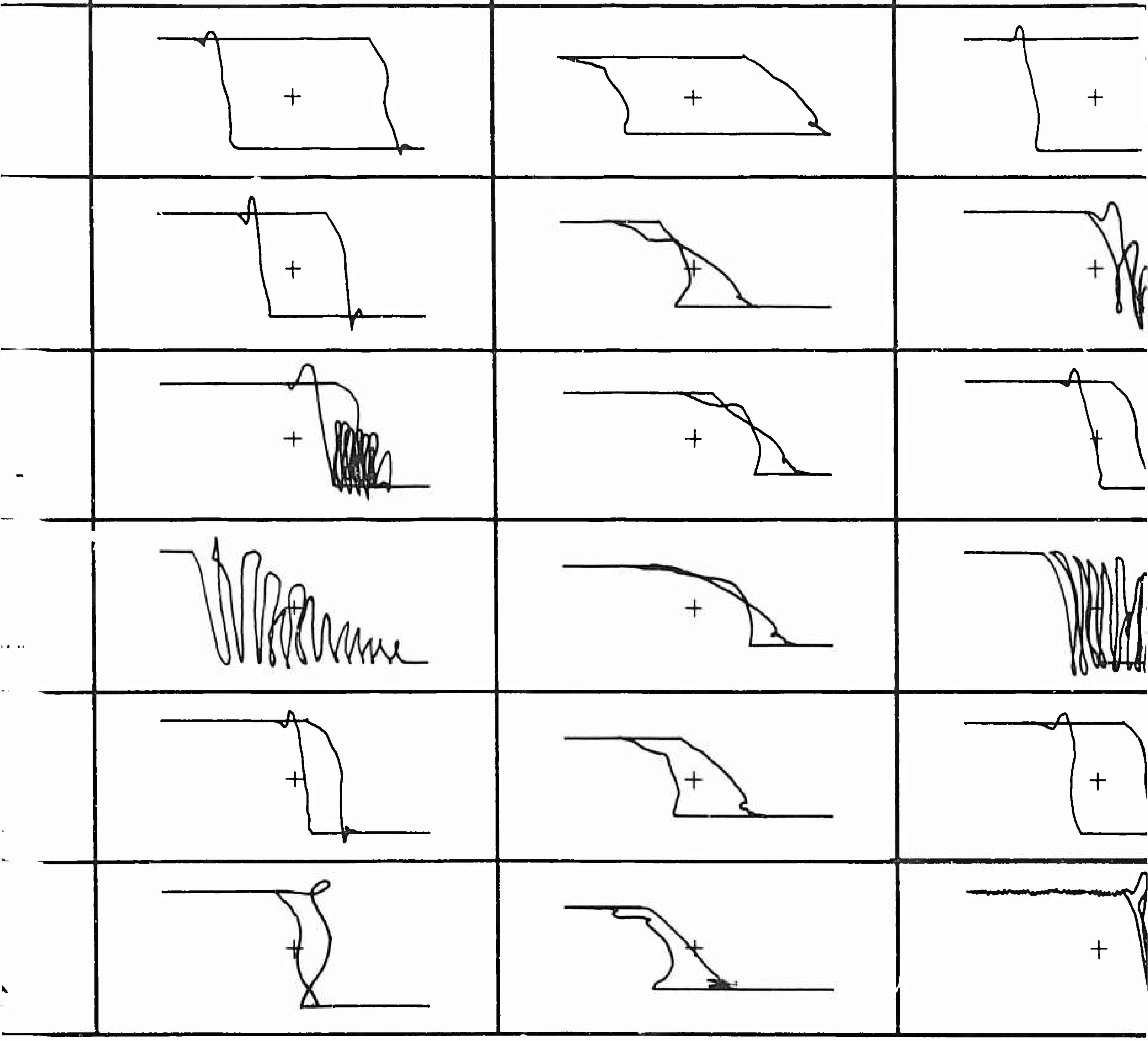


C

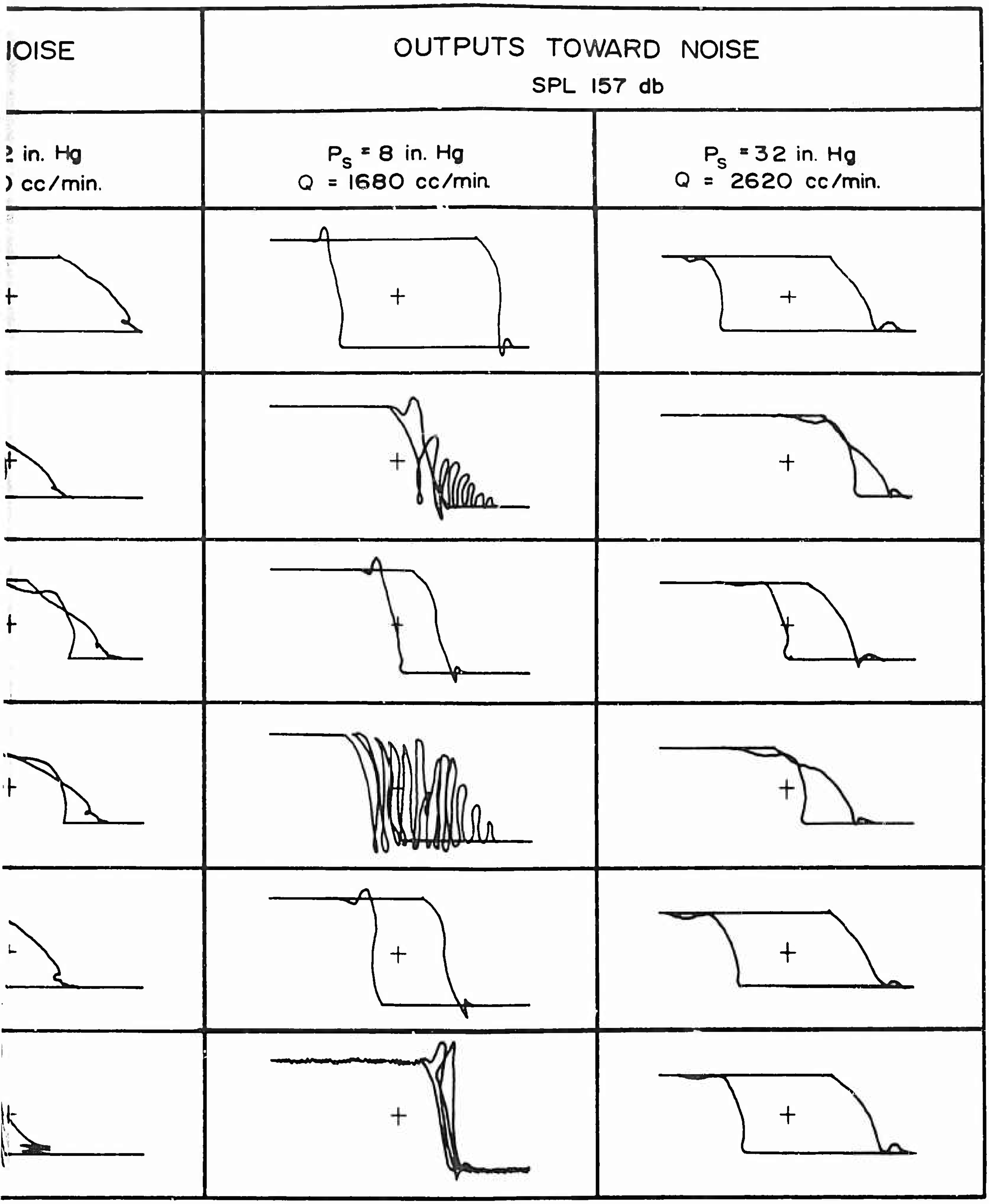
RIGHT CONTROL AWAY FROM NOISE

SPL 152 db

P_s = 8 in. Hg Q = 1680 cc/min.	P_s = 32 in. Hg Q = 2620 cc/min.	P_s = 8 in. H… Q = 1680 cc…



D



IOISE
2 in. Hg
) cc/min.
OUTPUTS TOWARD NOISE
SPL 157 db
P_S = 8 in. Hg
Q = 1680 cc/min.
P_S = 32 in. Hg
Q = 2620 cc/min.

E

CONF
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FIG. B-2

Scaled Reproduction of X—Y Recorder Data

"AMPLIFIER B"

ABSCISSA $P_{lc} - P_{rc}$

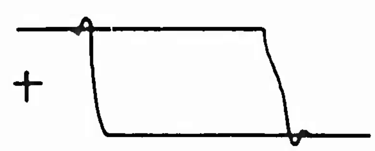
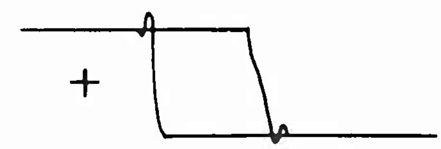
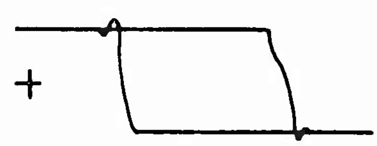
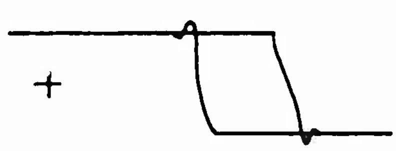
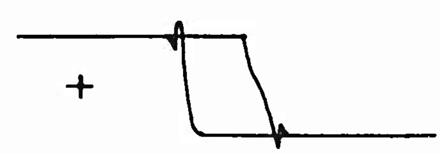
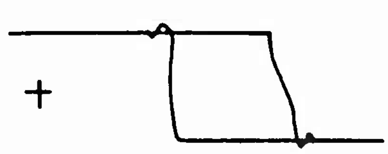
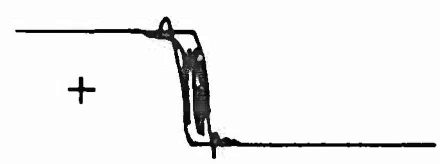
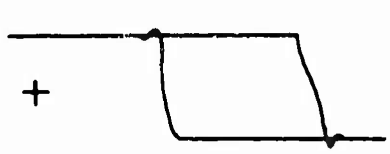
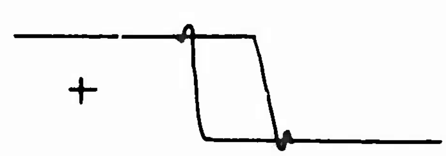
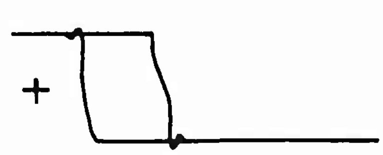
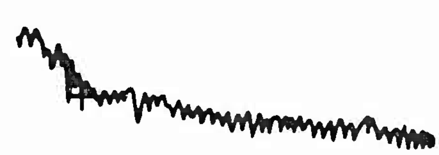
Scale: 1 in. = 0.3 in. Hg

ORDINATE $P_{lo} - P_{ro}$

Scale: 1 in. = 3 in. Hg

\+ INDICATES 0, 0

A

CONFIGURATION P_s Q SPL / f CPS	OUTPUTS TOWARD NOISE P_s = 4 in. Hg Q = 2160 cc/min.	
	SPL 151 db	SPL 157 db
0		
2000		
1000		
500		
200		
100		

B

Appendix C

Tabulated Data from X-Y Recorder

Table C-1

Amplifier A

Right Control Towards Noise

P_s=8 in. Hg, Q=1680 cc/min, SPL=152 db

f cps	ΔP_{c1} in. Hg	ΔP_{c2} in. Hg	Remarks
0	0.19	-0.17	Reference
100	-0.02	0.01	Unstable, ΔP_c=0.01 to 0.3
200	0.08	-0.15	
500	—	—	Behaved as proportional amp.
1000	—	—	Behaved as proportional amp.
2000	—	—	Behaved as proportional amp.

Table C-2

Amplifier A

Right Control Towards Noise

P_s=32 in. Hg, Q=2620 cc/min, SPL=152 db

f cps	ΔP_{c1} in. Hg	ΔP_{c2} in. Hg	Remarks
0	0.12	-0.17	Reference
100	-0.09	0.12	Unstable, ΔP_c=0.07 to 0.13
200	0.03	-0.19	
500	—	—	Oscillating
1000	—	—	Oscillating
2000	—	—	Oscillating

Table C-3

Amplifier A

Vents Toward Noise

P_s=8 in. Hg, Q=1680 cc/min, SPL=157 db

f cps	ΔP_{c1} in. Hg	ΔP_{c2} in. Hg	Remarks
0	0.20	-0.21	Reference
100	0.12	-0.18	
200	0.13	-0.19	
500	0.09	-0.14	
1000	0.13	-0.16	
2000	0.19	-0.19	Almost no effect

Table C-4

Amplifier A

Vents Toward Noise

P_s=32 in. Hg, Q=2620 cc/min, SPL=157 db

f cps	ΔP_{c1} in. Hg	ΔP_{c2} in. Hg	Remarks
0	0.11	0.21	Reference
100	0.12	-0.18	
200	0.08	-0.17	
500	0.03	-0.14	
1000	0.03	-0.12	
2000	0.09	-0.05	

Table C-5

Amplifier A

Right Control Away From Noise

P_s=8 in. Hg, Q=1680 cc/min, SPL=152 db

f cps	ΔP_{c1} in. Hg	ΔP_{c2} in. Hg	Remarks
0	0.19	-0.16	Reference
100	-0.05	0.02	
200	0.02	0.05	
500	-0.23	—	Unstable, ΔP_c=-0.2 to 0.25
1000	0.09	0.07	Unstable, ΔP_c=0.07 to 0.21
2000	0.05	-0.05	

Table C-6

Amplifier A

Right Control Away From Noise

P_s=32 in. Hg, Q=2620 cc/min, SPL=152 db

f cps	ΔP_{c1} in. Hg	ΔP_{c2} in. Hg	Remarks
0	0.13	-0.17	Reference
100	-0.07	-0.06	
200	-0.05	-0.06	
500	-0.03	0.15	
1000	0.04	0.16	
2000	-0.09	-0.04	

Table C-7

Amplifier A

Outputs Toward Noise

P_s=8 in. Hg, Q=1680 cc/min, SPL=157 db

f cps	ΔP_{c1} in. Hg	ΔP_{c2} in. Hg	Remarks
0	0.19	-0.14	Reference
100	0.09	0.15	Unstable, ΔP_c=0.15 to 0.23
200	0.06	-0.03	
500	-0.12	-0.06	Unstable, ΔP_c=-0.06 to 0.16
1000	0.04	0.00	
2000	-0.03	0.07	Unstable, ΔP_c=0.03 to 0.23

Table C-8

Amplifier A

Outputs Toward Noise

P_s=32 in. Hg, Q=2620 cc/min, SPL=157 db

f cps	ΔP_{c1} in. Hg	ΔP_{c2} in. Hg	Remarks
0	0.11	-0.16	Reference
100	0.11	-0.11	
200	0.11	-0.16	
500	-0.12	-0.06	Unstable, ΔP_c=-0.06 to 0.16
1000	0.05	-0.07	
2000	0.08	0.20	

Table C-9

Amplifier B

Outputs Toward Noise

P_s=4 in. Hg, Q=2160 cc/min, SPL=151 db

f cps	ΔP_{c1} in. Hg	ΔP_{c2} in. Hg	Remarks
0	0.34	0.11	Reference
100	0.17	0.09	
200	0.39	0.02	
500	0.34	0.02	
1000	0.33	0.24	
2000	0.35	0.14	

Table C-10

Amplifier B

Outputs Toward Noise

P_s=4 in. Hg, Q=2160 cc/min, SPL=157 db

f cps	ΔP_{c1} in. Hg	ΔP_{c2} in. Hg	Remarks
0	0.24	0.09	Reference
100	—	—	Behaved as proportional amp.
200	0.21	0.18	
500	0.15	0.16	Unstable, ΔP_c=0.15 to 0.18
1000	0.23	0.17	
2000	—	—	Behaved as proportional amp.

Appendix D

Detailed Description of Instrumentation

Detailed Description of Instrumentation

Quantity	Description
1	Flowmeter, Brooks Instrument Company, tube: r-2-15-B, float: stainless steel, range (air): 0-4550 cc/min.
4	Differential Pressure Transducers, Statham Instruments, Inc., model no. PM-60TC, ranges: ± 1, ± 2.5, ± 5, and ± 15 psid.
1	Differential Pressure Transducer, Consolidated Engineering Corp., type 4-312, range: ± 7.5 psid (tested linear to 17 psid).
2	DC Amplifiers, KIN TEL model 111BF, max. gain: 2000.
1	X-Y Recorder, Electro Instruments, Inc., Model 200.
1	Microvolt-Ammeter, Keithley Instruments, Inc. model 150A, range: 1 microvolt to one volt full scale.
1	Crystal Microphone, Chesapeake Instrument Corp., model no. NM-126.

VITA

Charles Jasper Hansen, Jr. was born [redacted] After attending elementary schools in Georgia and North Carolina, he was graduated in May 1952 from Georgia Military Academy, College Park, Georgia. He was appointed to the United States Naval Academy, Annapolis, Maryland, and in June 1956 he was graduated with the degree of Bachelor of Science. After receiving his commission as Lieutenant in the USAF, he entered active duty in June 1956. After completing navigation and electronic countermeasures schools, he served as an electronic warfare officer with the 11th Tactical Reconnaissance Squadron, Yokota AB, Japan, from February 1959 to February 1960. From June 1960 to May 1964, prior to attending the Air Force Institute of Technology, he was assigned as electronic warfare officer with the 62nd Bomb Squadron at Eglin AFB, Florida.

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